Origin of Enigmatic Hills in the Ross Sea, Antarctica

A Senior Thesis

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by

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Introduction

Antarctica is an isolated part of this planet, yet the history of this continent and its ice sheets is of global importance. The structural deformation, volcanism, and ice sheet history of the continent can be reconstructed through geological studies of surface topography and subsurface architecture. In Antarctica, where much of the continent is covered by water and ice, geophysical data from the Antarctic submarine continental shelf, which remotely senses the seafloor and the earth below it, is a fundamental part of reconstructing geological history. As part of the 2004 *Nathaniel B. Palmer*-0401 (NBP-0401) geophysical expedition, a geological enigma was identified on the Ross Sea floor off the Antarctic coast. Using multibeam sonar to map the bathymetry of the seafloor, a series of eight mysterious, subcircular hills about 500m below sea level were identified. Previous work has shown that this area of the continent was covered by an ice sheet during the Last Glacial Maximum (Shipp et al., 1999), so the hills could have been formed from deposition or erosion of sediment in subglacial features called drumlins. Geophysical data indicates that this region had volcanic activity in the past (Behrendt et al., 1996), so the hills could have formed by volcanic eruptions on the seafloor. Their distinctive circular shapes suggest they could be volcanic “tuya”, which are volcanic eruptions beneath ice caps (Mathews, 1947). My research entails analysis of the seafloor hills to determine whether these seafloor hills were 1) formed by a volcanic eruption under a grounded ice sheet or 2) they are formed of consolidated sediments that were deposited by an advancing ice sheet.

Geologic Setting

The Antarctic Plate

The tectonic plate on which the continent of Antarctica lies is surrounded by passive margins (Fitzgerald, 2002). Antarctica covers approximately the same area as the United States and Mexico combined. It consists of two continental blocks: East Antarctica and West Antarctica (Figure 1). The boundary between these two blocks occurs along the Transantarctic Mountains, which stretch about 3500 kilometers into the continental interior. East Antarctica is significantly larger than West Antarctica and represents what is presumed to be a stable cratonic region composed mainly of Precambrian metamorphic basement rocks from Archean to Neoproterozoic in age. West Antarctica is a combination of several smaller blocks that have undergone tectonic displacements in the Mesozoic-Cenozoic, and contain both volcanic and mountainous terrain. The continent is covered by an ice sheet that is estimated to be up to 4 km thick in some locations. Due to the thick ice sheet cover, direct geologic observations are limited, but the use of modern remote sensing technologies provides a tool to help reconstruct the geologic history of the Antarctic continent.

West Antarctic Rift System

The West Antarctic Rift System (WARS) lies below the Ross Sea, Ross Ice Shelf, and part of the area underneath the West Antarctic Ice Sheet in the Ross Embayment (Fitzgerald, 2002). The WARS is a huge extensional regime within the Antarctic plate that is over 3000 kilometers long and 800 kilometers wide. The WARS in the Ross Sea regions consists of multiple high and low blocks entirely below sea level (Figure 2). The rift basins are known as the Northern Basin, Victoria Land Basin, Central Trough, and the Eastern Basin. The highs are known as the Coulman High and the Central High. Most of the rifting activity took place in the Late Cretaceous between 105 – 85 Ma (Lawver & Gahagan 1994, 1995).

Figure 1: Map of Antarctica.
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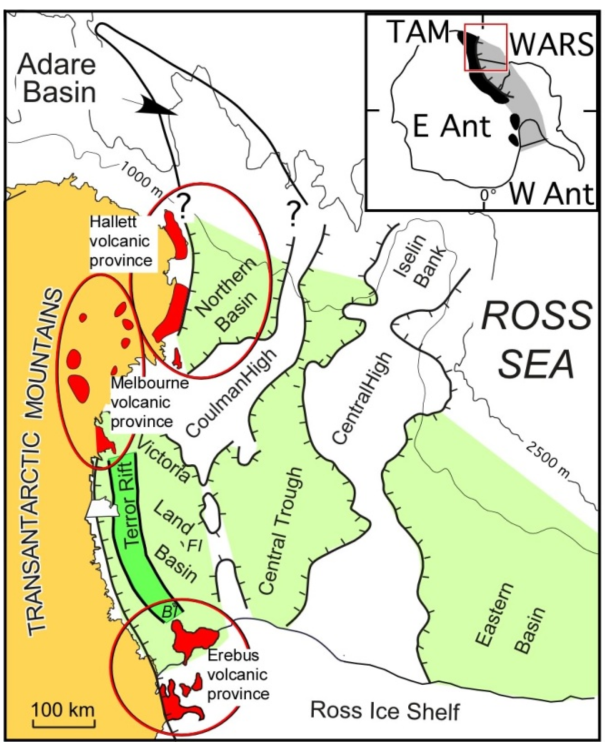


Figure 2: West Antarctic Rift System in the Ross Sea. Image courtesy of Terry Wilson.

Rift Structure Beneath the Western Ross Sea

About 85-105 Ma the Ross Sea began experiencing extension forming the Transantarctic Mountains and Ross Embayment (Fitzgerald, 2002). Most models say that the Northern Basin and Victoria Land Basin (Figure 4) in the western Ross Sea were developed during the Cretaceous (Cooper et al., 1987). It has been inferred that there was another rifting event in the Paleogene, with extension in the Victoria Land Basin, and uplift of the Transantarctic Mountains (Fitzgerald, 2002). The younger Terror Rift, which is a N-S trending extensional system, was superimposed on the Victoria Land Basin after about 30 Ma (Salvini, 1997) or, alternatively, in the Neogene after 17 Ma (Fielding et al., 2006). The Terror Rift was first defined by Cooper et al (1987) from seismic reflection profiles and divided into two components: down-faulted Discovery Graben and the volcanically intruded Lee Arch. There has been evidence for rift-related volcanism that post-dates the main stage of rifting in the central Terror Rift and may still be active today (Hall et al., 2007; Rilling et al., 2007).

Antarctic Plate Volcanic History

During the Cenozoic when the extension in the WARS became renewed it was confined to the western Ross Sea (Cooper et al., 1987). At this time there was abundant normal faulting and associated volcanic activity. Figure 2 shows the exposed localities of the rift-related Cenozoic volcanism arrayed along the western flank of the WARS (LeMasurier, 1990). The exposed volcanics primarily occur in the islands of the Ross Sea and in the Transantarctic Mountains. Additional evidence for volcanics that occur beneath the Ross Sea is derived from geophysical surveys, such as seismic profiles and magnetic anomalies. The seismic profiles show evidence for bodies cutting the sedimentary strata and forming seafloor hills (Cooper et al., 1987), and modeling of marine magnetic anomalies over the hills show that they are of volcanic origin (Behrendt et al., 1987). Regional aeromagnetic surveys are interpreted to show widespread submarine and subglacial volcanics in the Ross Sea (Behrendt, 1999) (Figure 4). Magnetic anomalies from aeromagnetic mapping show where rock bodies cause a magnetic signature that varies from the normal magnetic field of the earth. Volcanic rocks typically have a strong magnetic anomaly signature due to their higher ferrous content than most sedimentary rocks. The strong positive (red) and negative (blue) magnetic anomalies across the Ross Sea region indicate the presence of volcanic rocks at or beneath the seafloor (Behrendt et al., 1995).

<u>Erebus and Melbourne Volcanic Provinces in the Western Ross Sea Region</u>

The geologically best known volcanic province in the McMurdo Volcanic group is the Erebus Volcanic Province in the southwestern Ross Sea (Figure 5) (Kyle, 1990). The Erebus Volcanic Province (EVP) has been host to extensive late Cenozoic volcanism up to present. The EVP has volcanic centers as old as 18.7-15.5 Ma near the bases of Mount Morning and Mount Discovery. Mount Erebus is an active volcano (Figure 5) containing a phonolitic lava lake that regularly has low-level volcanic eruptions, known as Strombolian eruptions (Kyle, 1990). The other active volcano in the western Ross Sea region is Mount Melbourne. The Mount Melbourne Volcanic Field has evidence for Holocene volcanic activity as young as a few hundred years ago (Wörner and Viereck, 1990). It has been suggested that there has been young volcanic activity between the Melbourne and Erebus provinces within the western Ross Sea. A recent study by Rilling and others (2007) presents a new $^{40}Ar/^{39}Ar$ age on Franklin Island of 3.3-3.7 Ma and shows that volcanic cones on the surrounding seafloor are as young as 89-127 Ka. There is a known volcanic edifice on the seafloor approximately 11 km southeast of this study area. The majority of volcanism related to the EVP has been dated to be Plio-Pleistocene in age when volcanism became more extensive and widespread (Kyle, 1990).

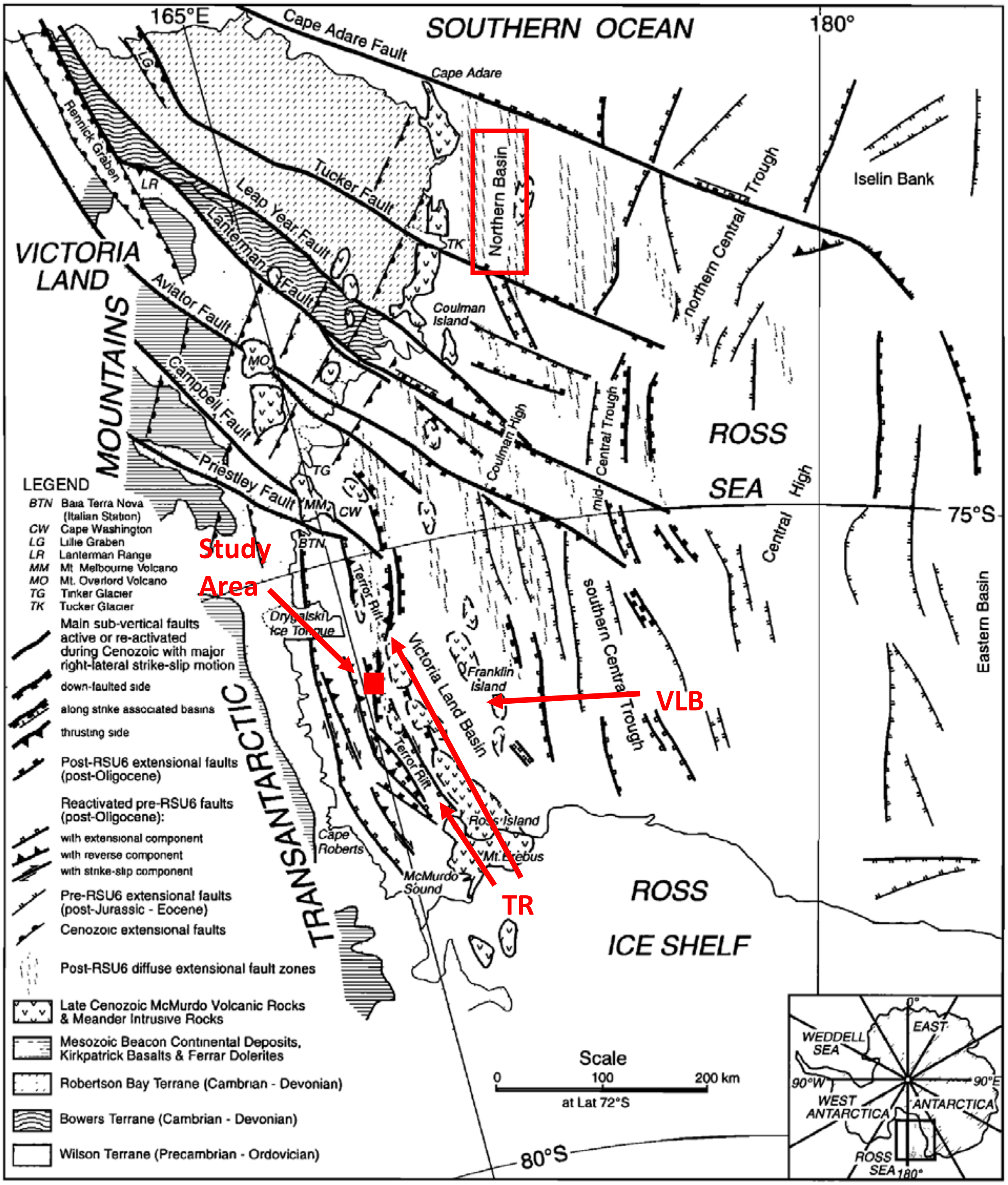


Figure 3: Fault patterns of the West Antarctic Rift System in the Ross Sea. VLB = Victoria Land Basin, TR = Terror Rift. From Salvini, 1997.

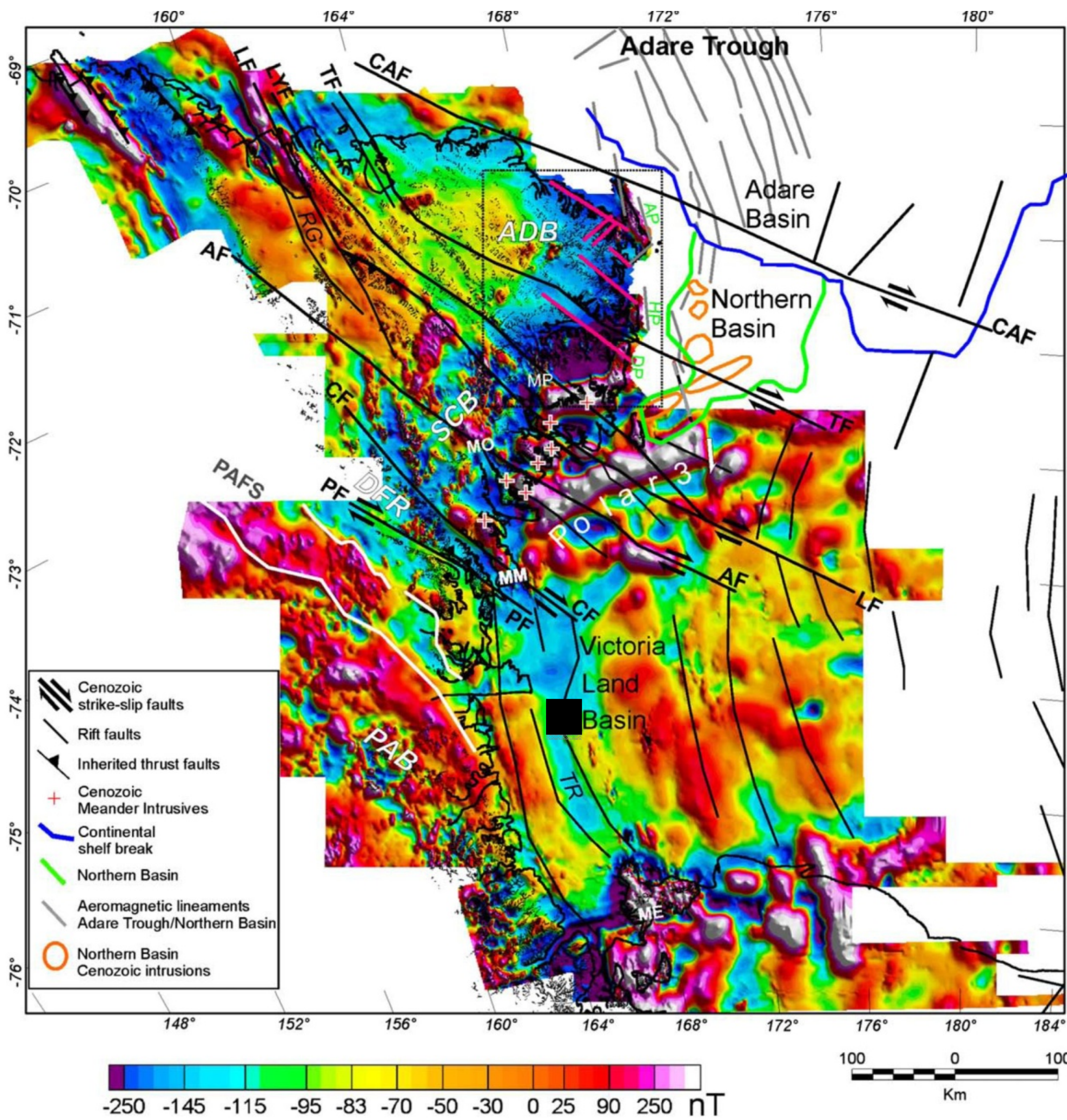


Figure 4: Aeromagnetic anomalies identifying magnetic signatures from the Ross Sea floor. (Ferraccioli et al., 2008) Black box indicates study area.

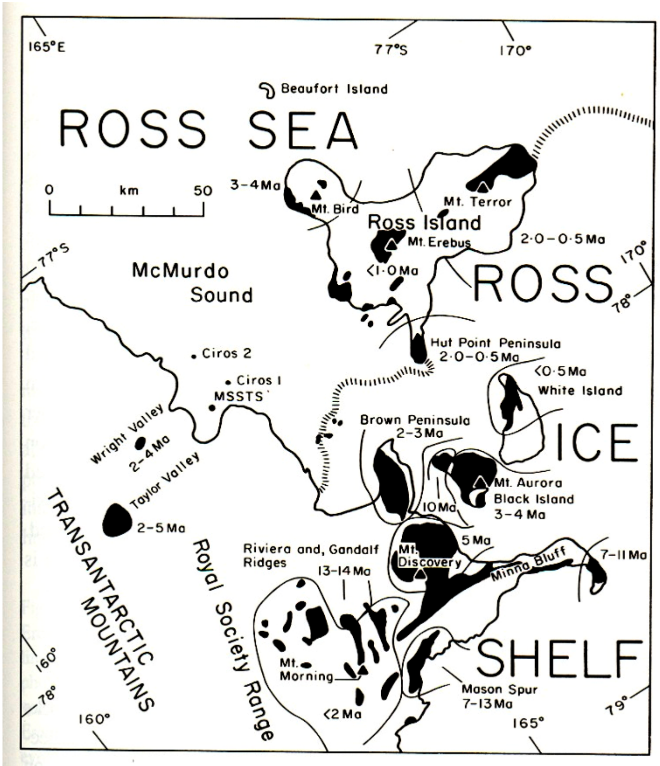


Figure 5: Major volcanic centers of the Erebus Volcanic Province. (Kyle, 1990)

Ice Sheet History

Ice sheets first developed on Antarctica during the Oligocene (Barrett, 2008). About 34 Ma marks a transition from relatively ice-free greenhouse conditions to "icehouse" conditions of today (Dunbar et al., 2008). A rapid global cooling event occurred at this time. Since that time, ice sheets repeatedly advanced and retreated from the southwestern Ross Sea region (Barrett, 2008), and there is evidence for multiple fluctuations of ice sheet advance and retreat throughout the Pliocene and Pleistocene From the AND-1B sedimentary rock core taken from underneath the McMurdo Ice Shelf (Naish et al., 2009).

To determine the extent of the ice sheet in the Ross Sea during the Last Glacial Maximum (LGM), it is crucial to use detailed bathymetric data, but little has been available from the polar seas. In the recent past there have been numerous geophysical cruises that have surveyed the Antarctic oceans and have obtained thousands of kilometers of accurate bathymetry data. From this bathymetry it is possible to recognize certain subglacial geomorphological features on the continental shelf seafloor. These features include iceberg furrows, drumlins, channels, and mega-scale glacial lineations. Based on the distribution of these features, it has been determined that at the Last Glacial Maximum (LGM) there was a grounded ice sheet that extended to the continental shelf edge of the central Ross Sea and about 150 km from the shelf edge in the western Ross Sea (Figure 6) (Shipp et al., 1999). This grounded ice sheet is thought to have come from an expansion of the West Antarctic Ice Sheet 11 ± 0.25 ka (Domack et al., 1999). The predominant flow direction for the ice sheet in the western Ross Sea is about N38°E (Figure 7), but ranges between N10°E and N50°E as shown by the elongation direction of drumlins and mega-scale glacial lineation alignment (Figure 7) (Shipp et al., 1999). Due to this recent evidence it can be inferred that features that lie on the Ross Sea floor may have been altered by the grounded ice sheet in its advance to its maximum extent around 11 ka.

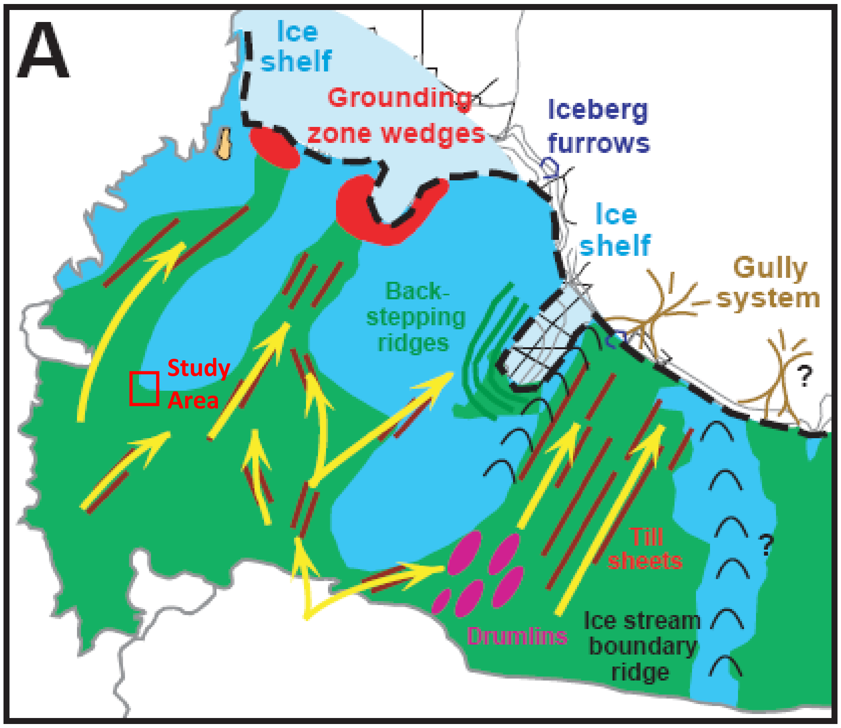


Figure 6: Maximum extent of ice sheet at last glacial maximum. From Shipp et al., 1999.

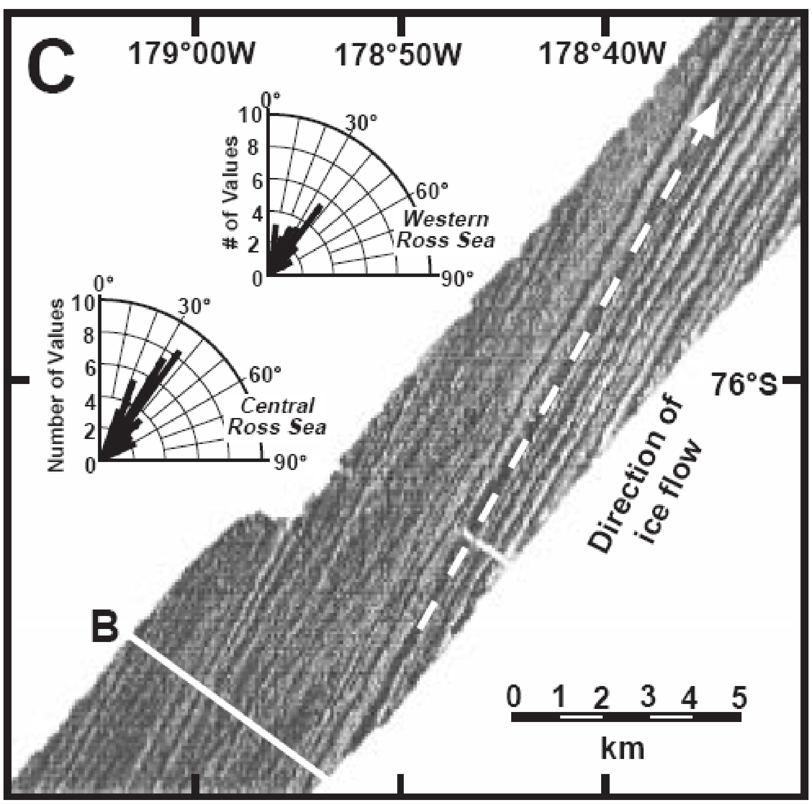


Figure 7: Orientation of mega-scale glacial lineations in the western Ross Sea. From Shipp et al., 1999.

Establishing the Origin of Seafloor Hills

Hypotheses for the Origin of the Enigmatic Seafloor Hills

On the 2004 NBP04-01 geophysical cruise there was approximately 3000 km^2 of continuous multibeam bathymetry coverage of the Ross Sea floor near McMurdo Sound (Lawver et al., 2007). There was also additional multibeam coverage to the north and west of Franklin Island near 75.5°S, 166°E. In this additional coverage area of approximately 300 km^2 a series of eight subcircular hills were discovered on the seafloor (Figure 8). Due to this area of the Ross Sea being overlain by grounded ice sheets in the past (Shipp et al., 1999), it is suggested that these features were either formed or shaped by a previous ice sheet. This leads to two potential origins of the mounds: 1) these seafloor hills were formed by subglacial erosive processes which left behind consolidated sedimentary structures called drumlins, or 2) the hills were formed by subglacial volcanism under the grounded ice sheet to create volcanic features known as tuyas.

Approach to Testing Hypotheses

In order to gain a further understanding of the possible origins of the seafloor hills their surface morphologies are characterized using a 3-dimensional bathymetry visualization software, IVS Fledermaus©. The morphological attributes of the hills are compared to known characteristics of drumlins and tuyas. A drumlin has a characteristically streamlined, teardrop form when observed in map view. It has a higher stoss side and a tapering lee slope in the direction of flow. On the contrary, a tuya has a relatively subcircular to elliptical shape in map view with a characteristically flat top and steep-sided morphology. Identification of these attributes on the seafloor hills will be used to test which hypothesis of their origin is valid.

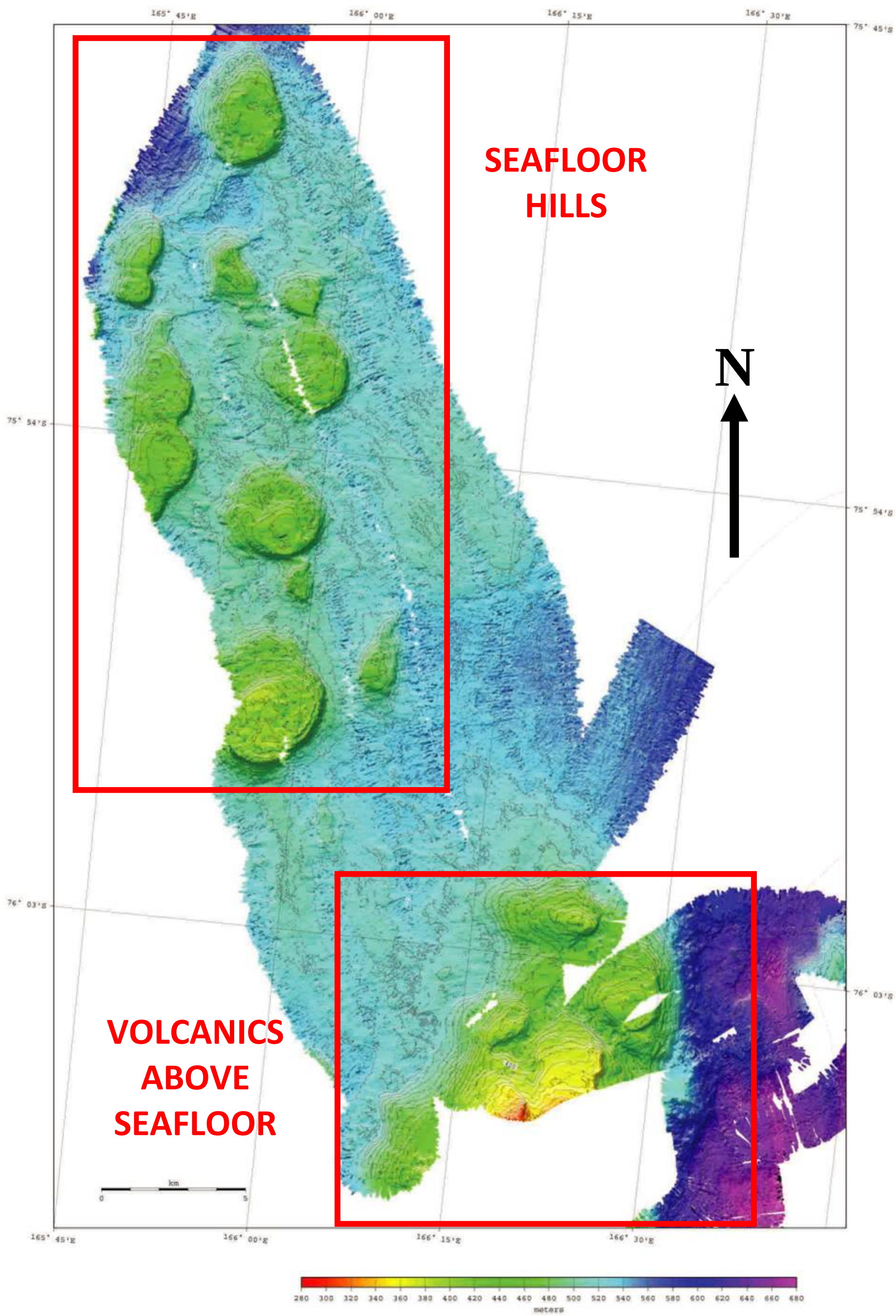


Figure 8: Enigmatic hills identified on the Ross Sea floor.

Drumlin Morphology

The term *drumlin* is from the Gaelic word *druim*, meaning a rounded hill (Menzies, 1979). Drumlins are mounds of accumulated sediment that are formed by glacial action below the ice. The typical morphology of a drumlin is ovoid-shaped, resembling half of a buried egg along the long axis (Menzies, 1979). The height of drumlins is variable. They can be anywhere from a few meters up to about 75m at the highest point. With respect to length they can be anywhere from 100m to upwards of a few kilometers on the long axis. Along the short axis their typical widths are anywhere from 50m to 500m. A rule of thumb that is suggested is that drumlins are typically three times as long as they are wide. However, this is skewed due to some drumlins being as much as ten times longer than they are wide.

While numerous theories exist for the formation of drumlins, a lack of modern-day observations of subglacial environments makes a conclusive classification difficult. The process of drumlinization is still widely debated, but a popular theory by Menzies (1979) suggests two possible modes of formation: depositional or erosional. Depositional formation involves the soft sediment deformation of accumulated till, as “sticky” points develop on the bottom of the ice bed. These points act as obstacles for the overlying ice sheet, causing sediment accumulation. The erosional formation is described by Hart (1995) as the interaction of basal meltwater with more competent pre-existing sediment, boulder piles, or bedrock protrusions. The glacial advance over these resistant lithologies will begin to form a subglacial cavity. This cavity will then begin to fill with meltwater and begin to deposit sediment. Water pressures in the cavity determine the deposition of this sediment. With higher water pressures, determined by a less-resistant knob, the cavity will fill with deforming till. Lower water pressures, with a more-resistant bedrock knob, will allow the cavity to fill with fluvial sediments around the bedrock knob.

The internal composition of most drumlins is primarily unconsolidated sediment or till. Within the drumlin core it is a poorly sorted till with various clast sizes. This composition is characteristic of depositional drumlins. However, numerous drumlins have been found with a rock core mantled by a *carapace* of till, surrounding the core like an eggshell (Benn et al, 1998). The drumlins with a carapace of till are characteristic of erosional drumlins. Drumlins tend to be concentrated in fields numbering into several thousand individuals (Benn et al, 1998). Figure 9 shows drumlins found on a bathymetric image that can be described as a strong surface return with a hummocky external geometry (Shipp et al., 1999; Wellner et al., 2001).

Drumlins are typically identified by morphology rather than internal composition (Hill, 1971). Long axes are oriented parallel to the direction of ice flow, with the stoss or higher and wider ends facing the direction from which a glacier moves, and the lee, or pointed ends facing the direction toward which the glacier is flowing (Figure 13). Drumlin change in elevation is aligned with the direction of flow, with summits located closest to the glacier source and lower elevations located at the opposite end of the feature, farthest from the glacier source (Benn et al, 1996). They are classified into several shapes, with the most common being *spindle, parabolic,* and *transverse asymmetrical*. Spindle-shaped drumlins are recognized by being long and narrow, whereas parabolic forms are often asymmetrical (Shaw, 1983). Transverse asymmetrical drumlins have a much more complex shape and are not as easily recognized.

Tuya Morphology

Mathews (1947) was the first to fully describe the morphology of flat-topped, steep-sided volcanoes in British Columbia. He named these structures *tuyas,* which means, "table

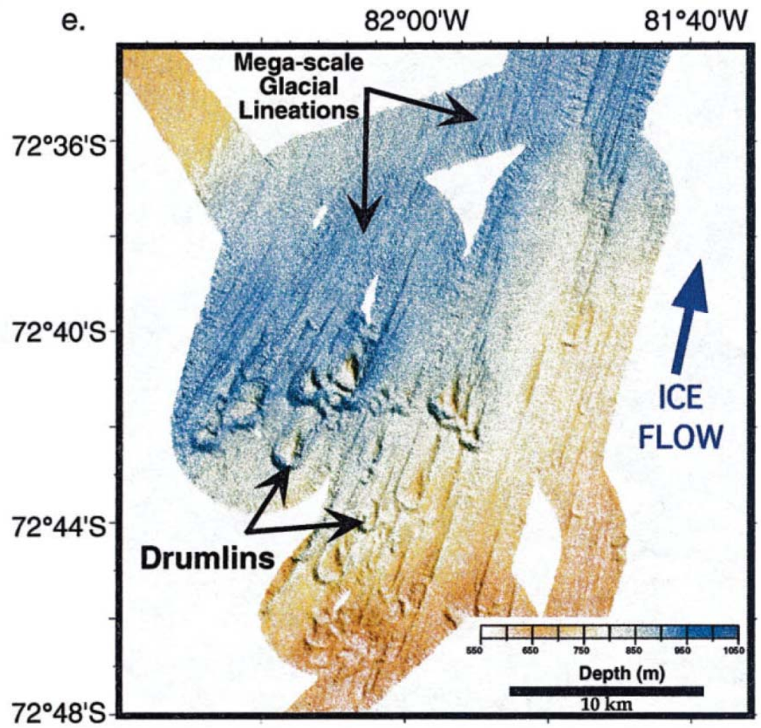


Figure 9: Drumlins identified on the Eltanin Bay floor. (Wellner et al., 2001)

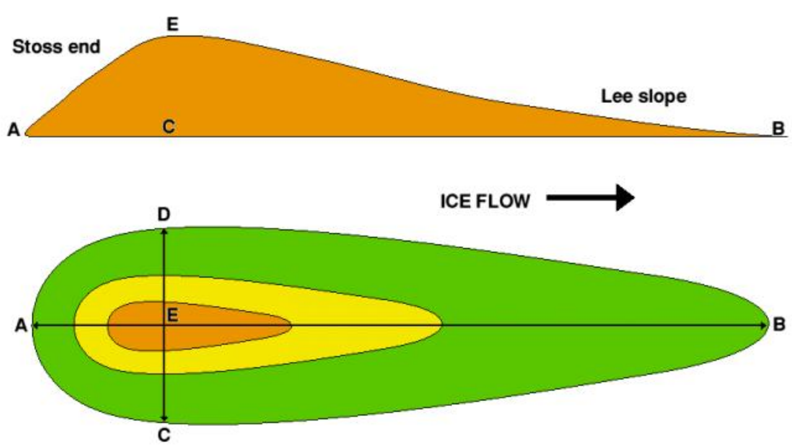


Figure 10: Cartoon of drumlin morphology. Image courtesy of www.geography-site.co.uk

mountain." Tuyas are formed when volcanism occurs subglacially. A typical tuya is roughly circular to elliptical in map view (Figure 11) and can rise up several hundred to a few thousand meters above its base (Figure 12). Their width can be anywhere from a half a kilometer to nearly 5 km.

The formation of a tuya is a complex process consisting of multiple stages (Figure 13). The core of tuyas consists of pillow lava formed when hot lava comes in contact with the melting ice and the lava is quickly cooled in the form of 'pillows.' The pillow lavas mainly dip steeply outward away from the central volcanic vent. As the growing volcanic edifice melts the surrounding ice mass, the glacial roof above begins to form a bowl-like depression. Once the ice above can no longer hold, it collapses and creates an intraglacial lake. Pillow lava basalts and hyaloclastites are continuously formed until the eruption breaches the lake's surface. Once this occurs, tuff and hydroclastic tephra are then deposited directly above the pillow lava, extending to the walls of the ice. The next layer is flow-foot breccias, with the flow moving away from the vent and outward along the lake surface. The eruption can then be capped by a broad, dome-shaped flow-foot breccia, similarly to a shield volcano. After this phase, the eruption beings to cease and over time, the glacier will withdraw, leaving the characteristic tuya form. Tuya size directly reflects the size and shape of the thickness of the confining ice and type of eruption. The two most common eruption types are a central vent or fissure-fed eruption. Hence, an eruption from a single, conical edifice will create the characteristic subcircular to ellipsoidal geometry. Smellie (2006) proposed that below the flat-topped surface of most tuyas, there must be horizontal columns, similar to columnar jointing, oriented perpendicular to the cooling surface. Another type of subglacial eruption is a fissure-fed eruption that will form what is called a "hyaloclastite ridge" or "tindar." In the developing stages of a tuya, there is an effusive stage

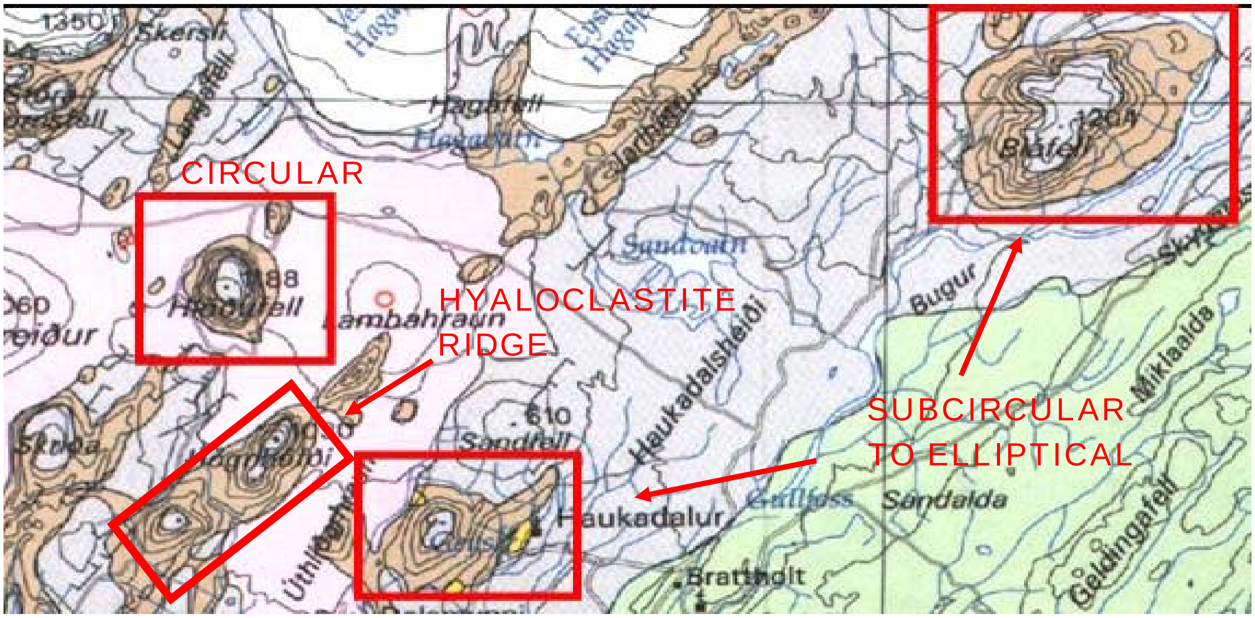
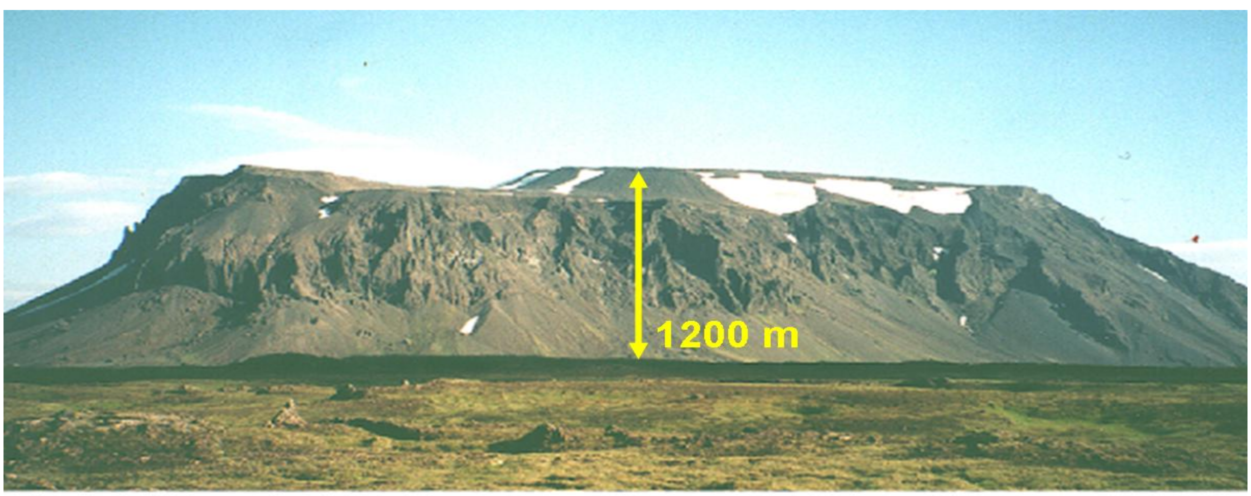


Figure 11: Tuyas and hyaloclastite ridge in map view in Iceland. Note the relatively circular, ellipsoidal, and elongate shapes. From Icelandic Institute of Natural History.



Hlodufell Tuya, looking East. Courtesy of Mary Chapman (USGS)

Figure 12: Hlodufell Tuya in Iceland rising over 1000 m in height. Steep-sided and flat-topped.

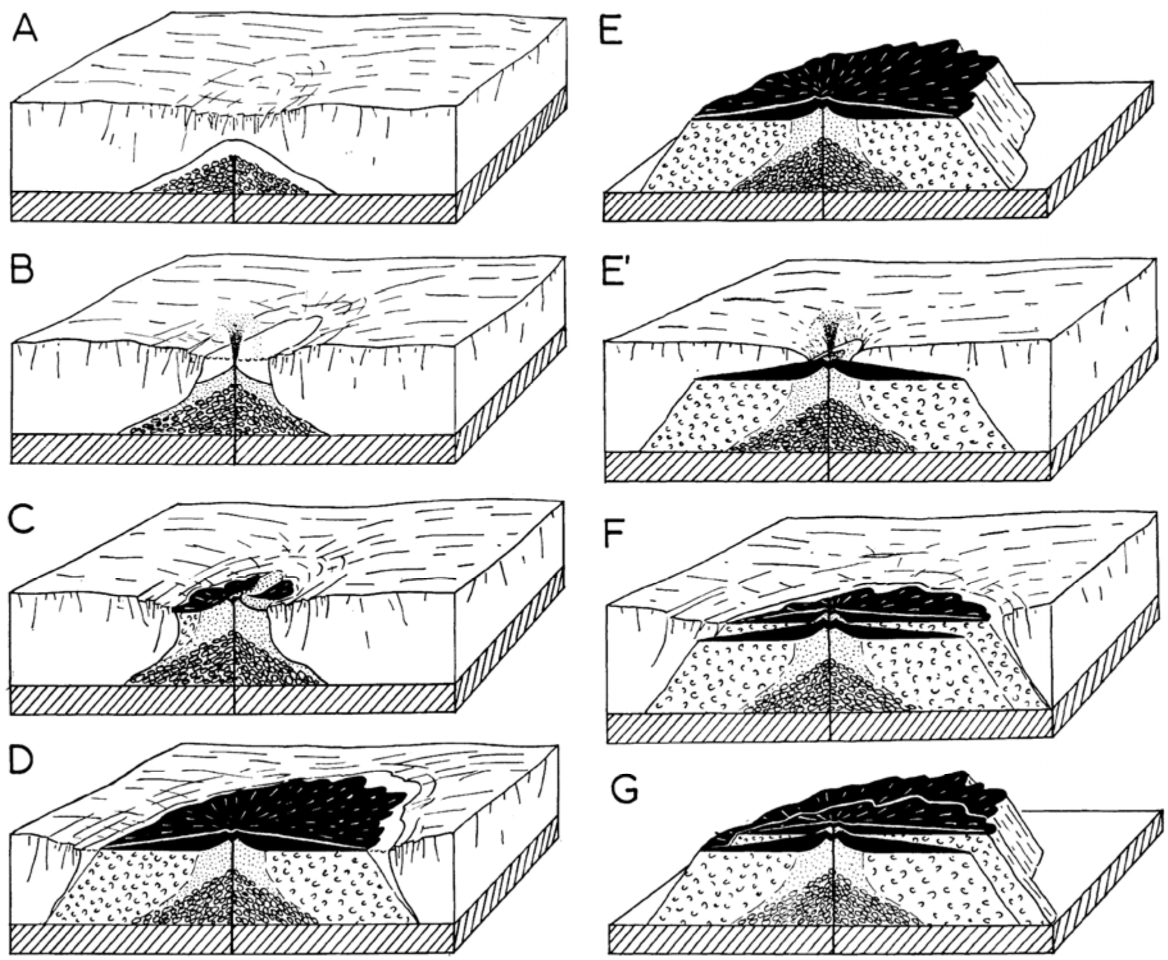


Figure 13: Cartoon of the formation of a tuya. Image from Jones, 1968.

known as a “tindar stage.” In some cases, eruption ends at this phase, to form a tindar. Therefore, a tindar is a short-lived subglacial eruption that forms a low ridge along the fissure, lacking the high elevation and flat tops of tuyas. Their internal composition predominantly consists of hyaloclastite material. A hyaloclastite ridge has a steep-sided, linear geomorphology that results from the fissure-fed eruption (Figure 11).

The most extensive studies of subglacial eruptions have occurred in the highly volcanic regions of Iceland and British Columbia (Mathews, 1947; Jones, 1968; Bennett et al, 2006; Björnsson, 2002). Just recently in 1996 there was a subglacial eruption underneath the Vatnajökull Ice Cap in Iceland. Before the ash plume of the Gjálp eruption there was a lake formed on top of the ice sheet in the bowl-like depression as well as development of extensive subglacial meltwater. The eruption caused a magnitude 5 earthquake and a subglacial outburst flood. The quantity of water that was discharged was similar to Niagara Falls, approximately 3,000,000 m^3/min, over the course of a few days. The significance of this discharge is that it has the potential to alter the surrounding landscape.

Summary

Using the surface morphologies of the seafloor hills it is possible to gain a better understanding of how they formed. Tuyas typically have height ranges between a few hundred to 1500 m, whereas drumlins are on the order of 10 m – 75 m. In a horizontal sense tuyas are several kilometers across and drumlins are 100 m – 1000 m in length. The heights, diameters, slopes, and map view characteristics are significantly different for drumlins versus tuyas, providing a means to test the hypotheses by comparing them with morphological data from the seafloor hills. The unique surface morphologies of the seafloor hills will allow interpretation of the history of the Ross Sea floor in this particular area.

Bathymetric Data

On the NBP04-01 geophysical cruise, bathymetry data was collected throughout the cruise. The system that was used was a multibeam swath sonar system, Konigsberg-Simrad EM 120, which was mounted to the hull of the ship. The advantage to having a swath multibeam system is that the bathymetry coverage is acquired over a wide swath, not just directly below the ship. This specific model has an angular coverage of up to 150 degrees from the ship's hull. With this angle there is lesser swath coverage in shallower water depths, but coverage is increased in deeper water. By obtaining a swath of data across this large angle, a much more extensive survey of the marine floor can be recorded in much shorter period of time (Figure 14).

Sonar systems use sound waves to map seafloor bathymetry. The system emits sound waves, or "pings," and records the time it takes for the sound to return. The depths are then determined from the delay between emission and reception. The EM 120 sends out up to 191 sonar beams per ping to map a swath of the seafloor. A large majority of the sound waves are reflected directly from the seafloor, however, the sonar beams also commonly return from other objects (specifically sea ice on this cruise), creating visible outliers in the raw bathymetry data. To remove these errors, the outliers are removed manually from files recording each sonar beam by the scientific crew aboard the ship. The particular software that was used to edit the EM 120 bathymetry data was called MBsystem; the specific program was "MBedit."

Since only minimal editing took place onboard the ship, a 3-dimensional bathymetry visualization software, IVS Fledermaus©, was used to further edit the multibeam soundings. The original XYZ data from the cruise was edited using a complex algorithm called CUBE within the program. This algorithm is used as a data-cleaning tool and can eliminate sounding blunders or noise and produce a much smoother surface (Mallace and Robertson, 2007). The use of the CUBE algorithm significantly improves the time it takes to edit the soundings and spend more time on interpretation. When editing the data it is possible to see the resultant surfaces and examine the individual soundings (Figure 15). While visualizing this on the XYZ coordinate system it is possible to delete soundings that are considered “noise” and a cleaner visualization of the bathymetry can be observed. The formed surface from the CUBE algorithm is colored in shades of blue in Figure 15 and the identified anomalous soundings are shown in red. While manually editing this surface, the outliers are ‘flagged’ or selected for removal (red points with crosshairs). This editing gives accurate depth measurements on maps and in profiles.

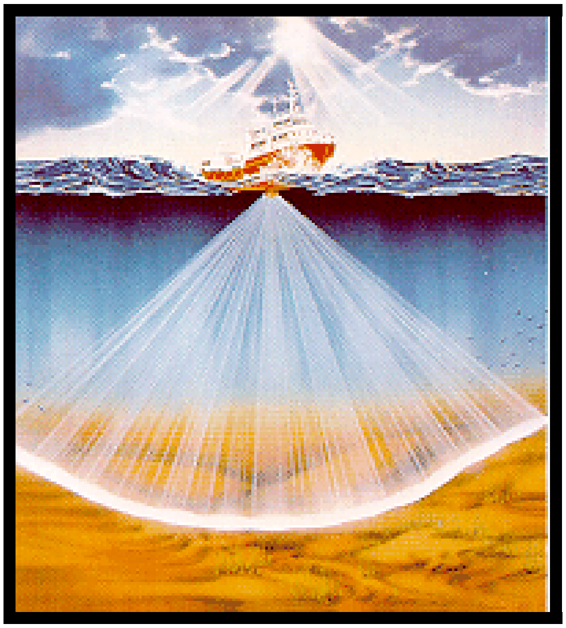


Figure 14: Cartoon of the acquisition of swath bathymetry. Image from gsc.nrcan.gc.ca

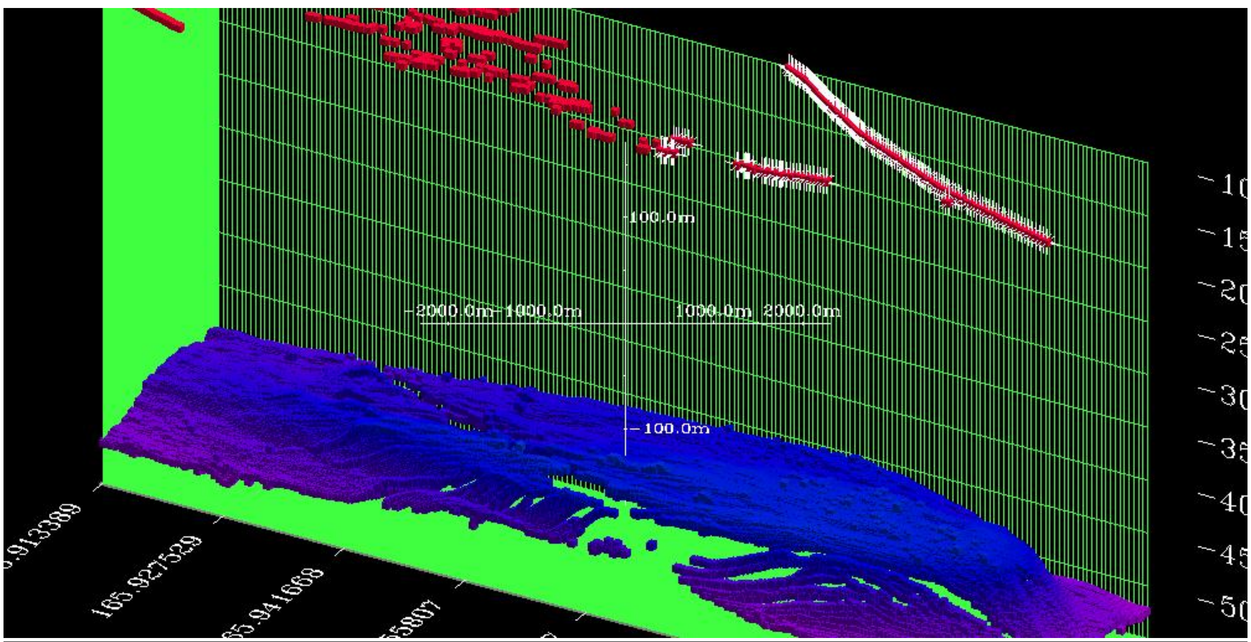


Figure 15: Screen shot of the manual and CUBE based editing in IVS Fledermaus©. Blue points are the true surface where red points have been rejected by the CUBE algorithm. Red points with crosshairs have been selected for removal.

Results

<u>Dimensions of the Seafloor Hills</u>

Observations were made using IVS Fledermaus© to visualize and make measurements from the bathymetry data. The three-dimensional capabilities of this software package allow surface morphologies of the seafloor to be seen in much better detail than a bathymetrical contour map. Dimensions of the seafloor hills were analyzed by making cross sections with map distance on the X axis and height on the Y axis.

Figure 16 shows the locations of cross section profiles constructed across the mounds along their longest and shortest dimensions. Horizontal dimensions were measured from the break in slope on either side of the hill. The cross section transect through the southernmost mound, A-A’, reveals a diameter of approximately 5500 m trending close to north-south. In the east-west direction AA-AA’ stretches at least 3000 m, but since the bathymetry data is cut off to the west of the hill we do not know the true diameter. When observing the section line of B-B’ the hill spans about 4000 m and the line perpendicular, BB-BB’, has the smallest span of only 1500 m. The section line C-C’ shows a diameter of a little more than 3000 m north-south, with an east-west diameter of approximately 3000 m as well. The section line from D-D’ shows the greatest north-south dimension of just over 8000 m and just over 2000 m east-west from DD-DD’. The other three hills have horizontal profiles that fall within the scale of the largest and smallest mentioned above. The horizontal scale of several kilometers for the seafloor hills is most similar to the size of a tuya.

The hills were then described on the vertical scale; measured from the greatest elevation of the hill to its break in slope at the base. There is a vertical exaggeration of 6:1 on the profiles, but the vertical and horizontal scales show true dimensions. The greatest height of any of the

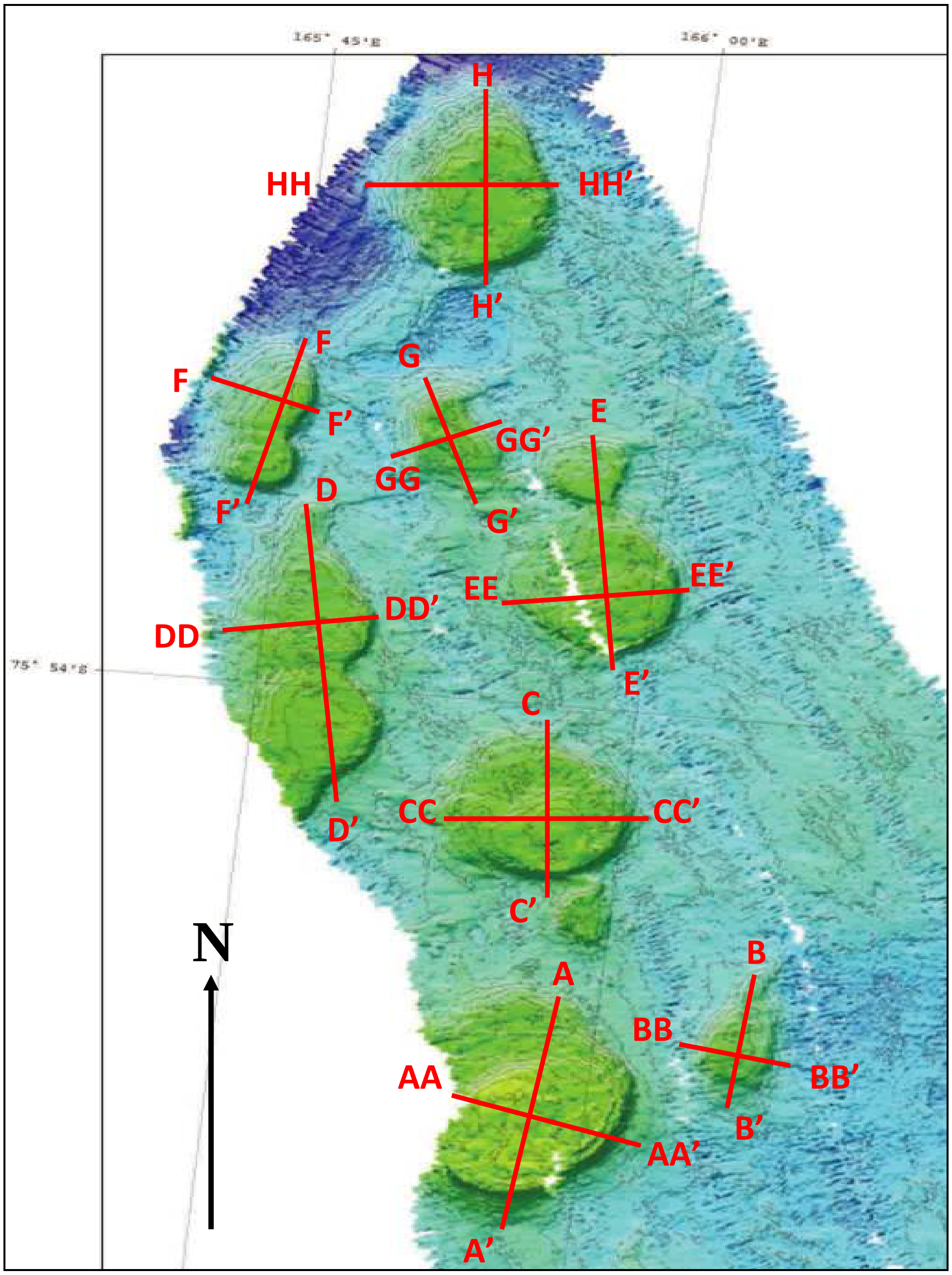


Figure 16: Cross section profiles through three seafloor hills. All distances are measured in meters. The colors of the profiles represent the Fledermaus© color bar for depth. The black segments in profiles represent voids in the bathymetry data. Vertical exaggeration is 6:1.

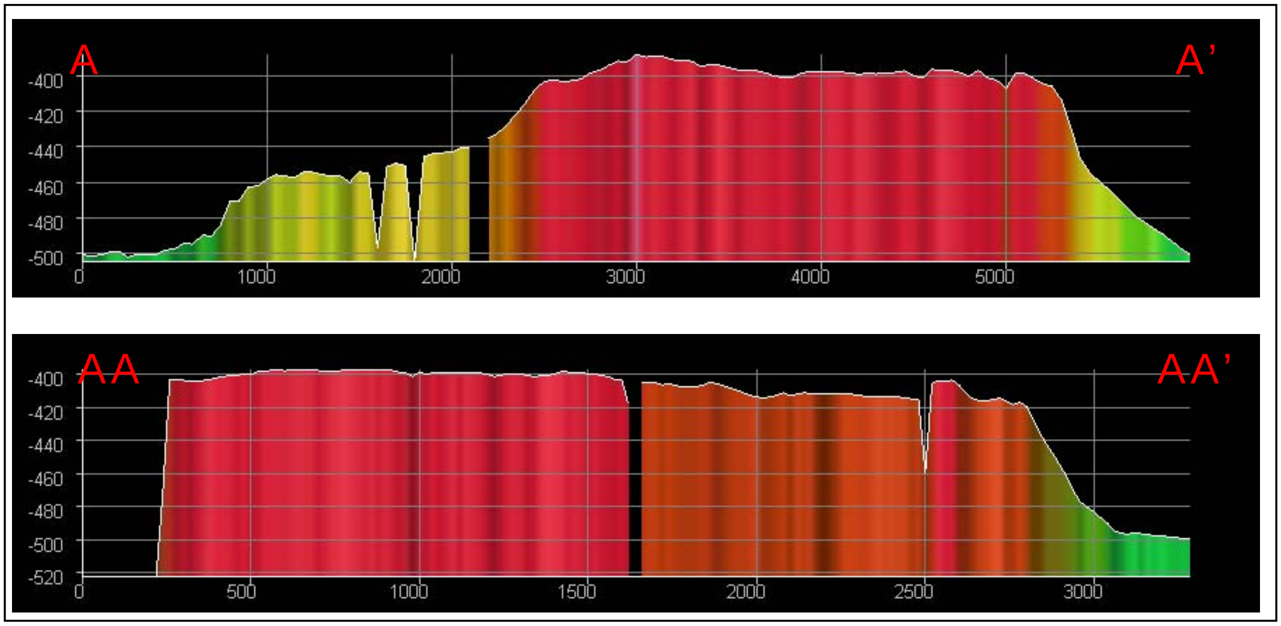


Figure 16A

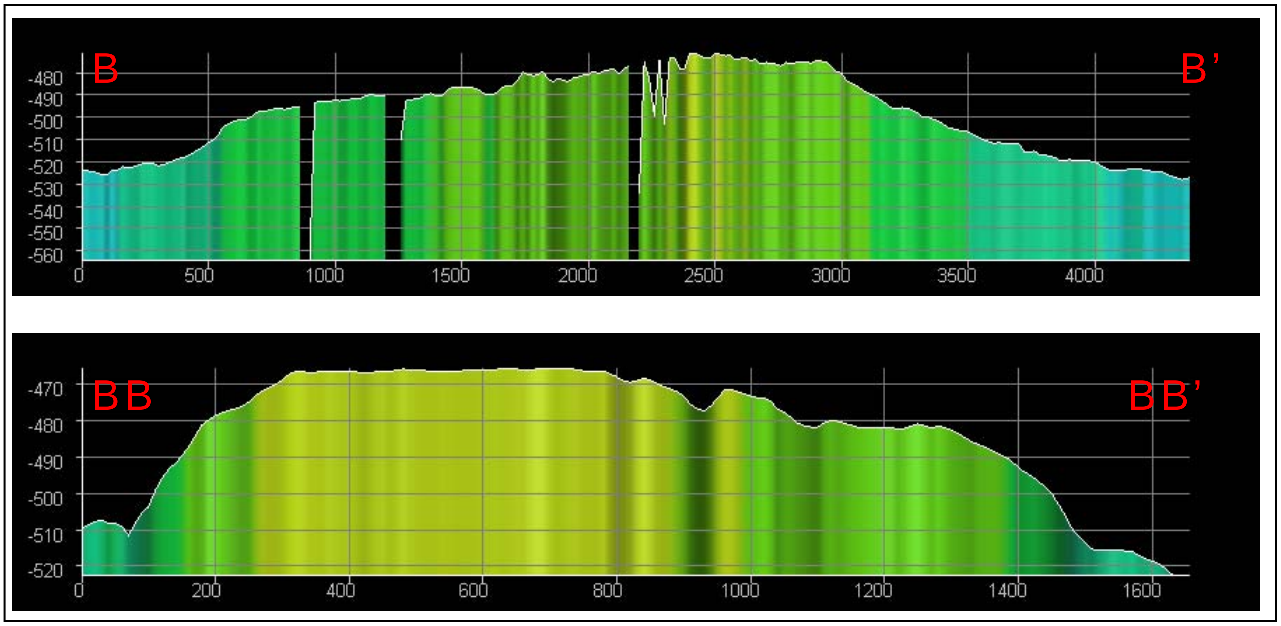


Figure 16B

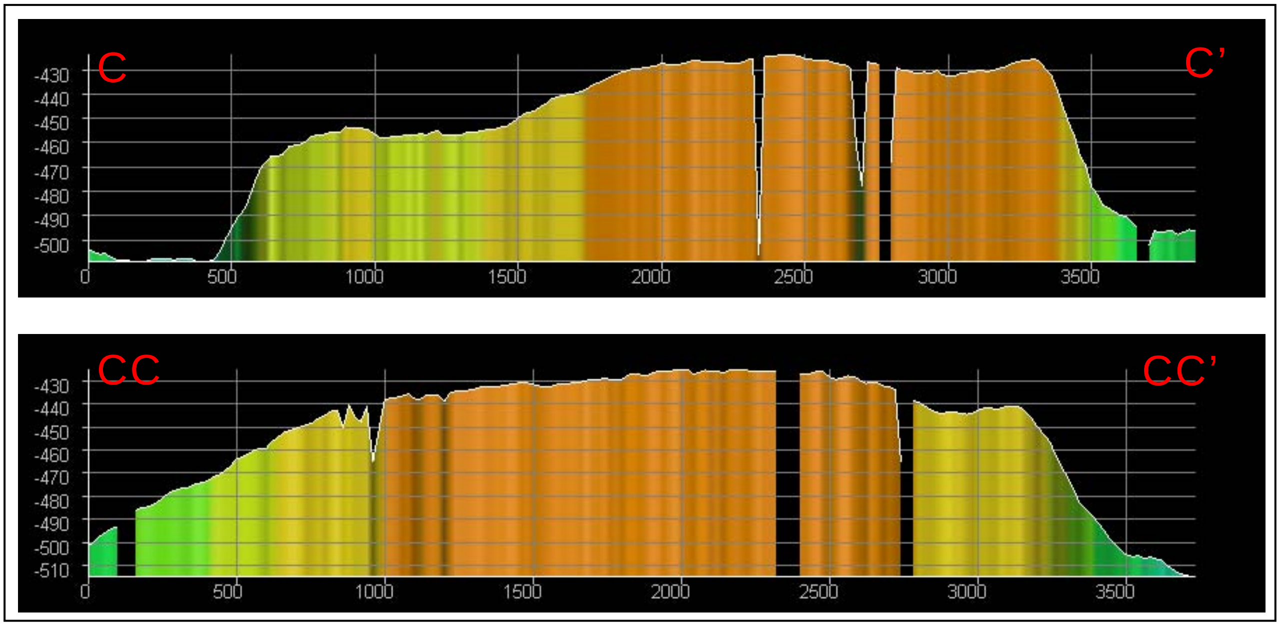


Figure 16C

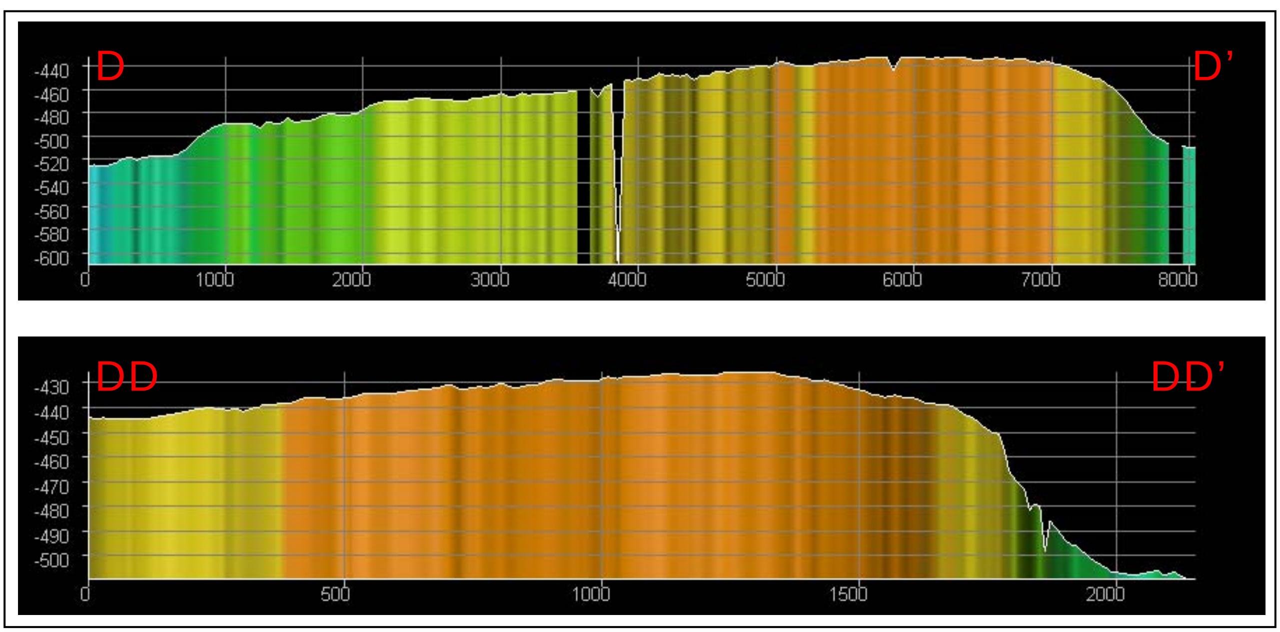


Figure 16D

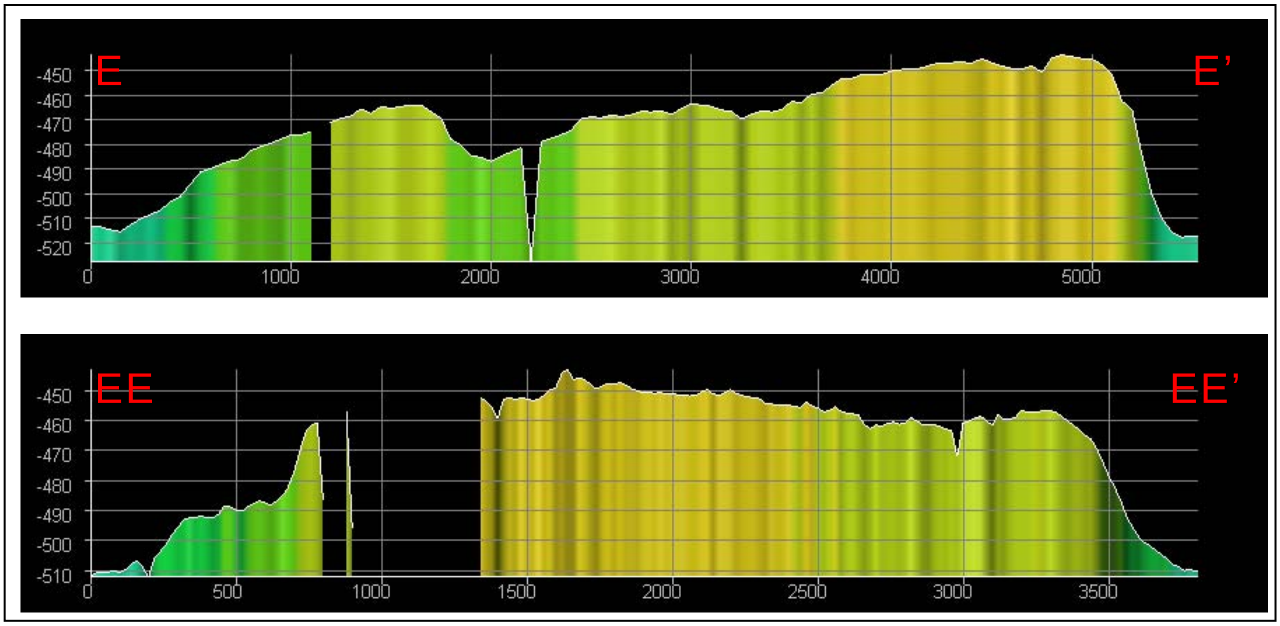


Figure 16E

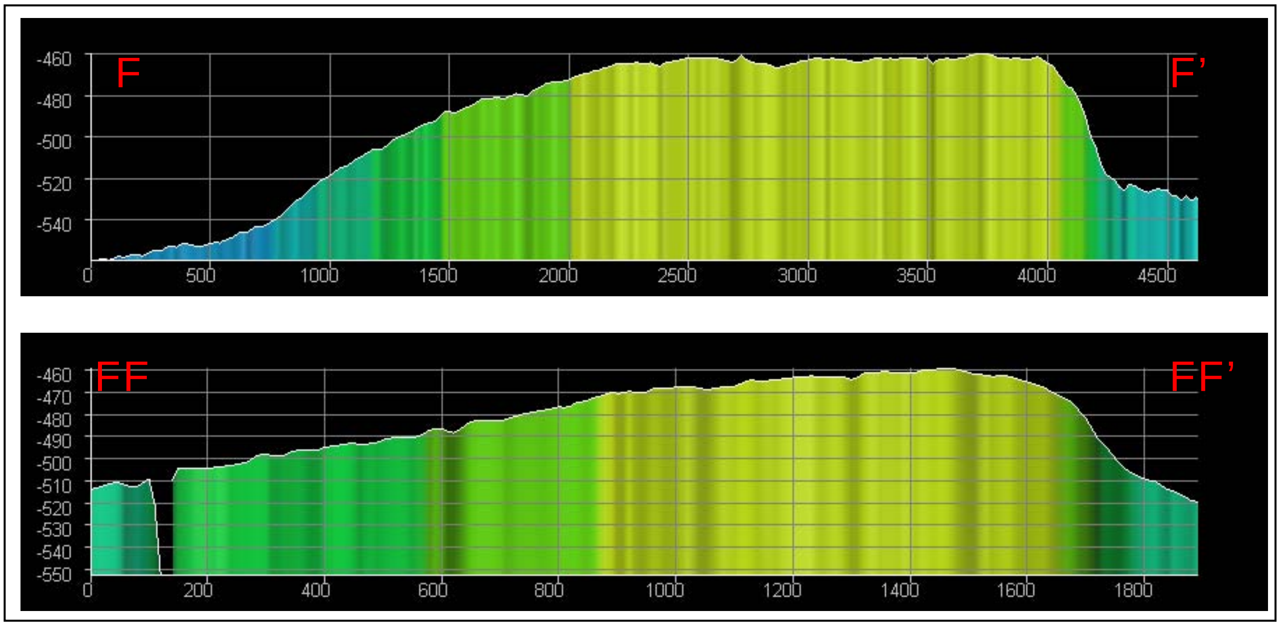


Figure 16F

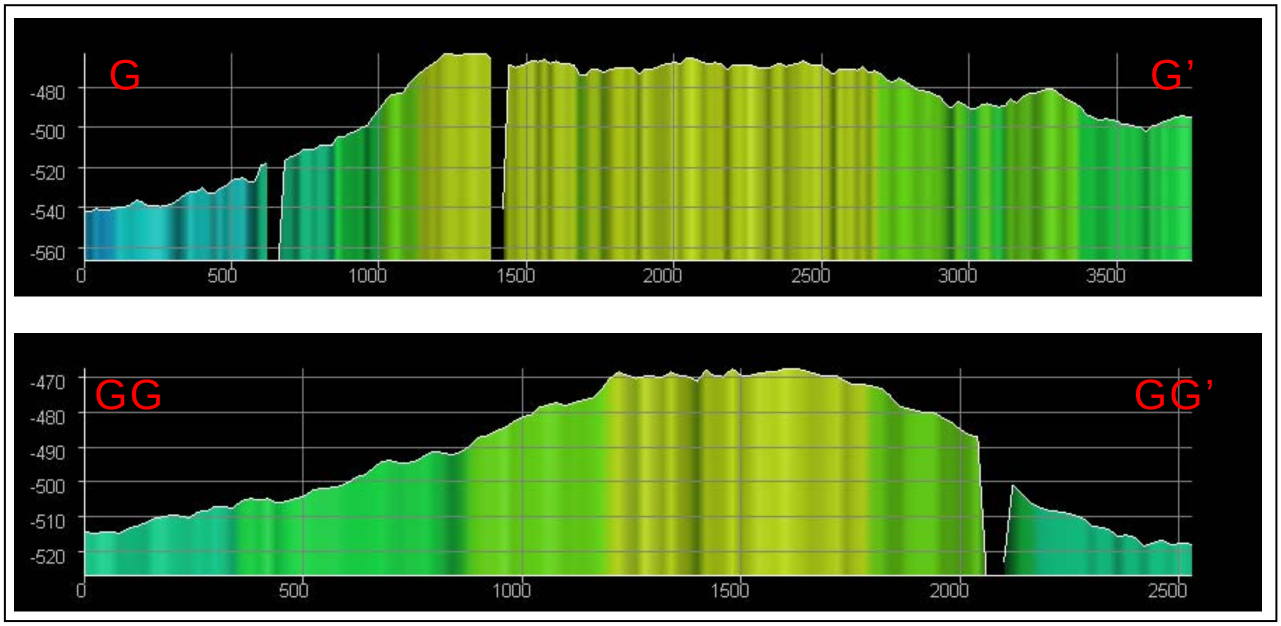


Figure 16G

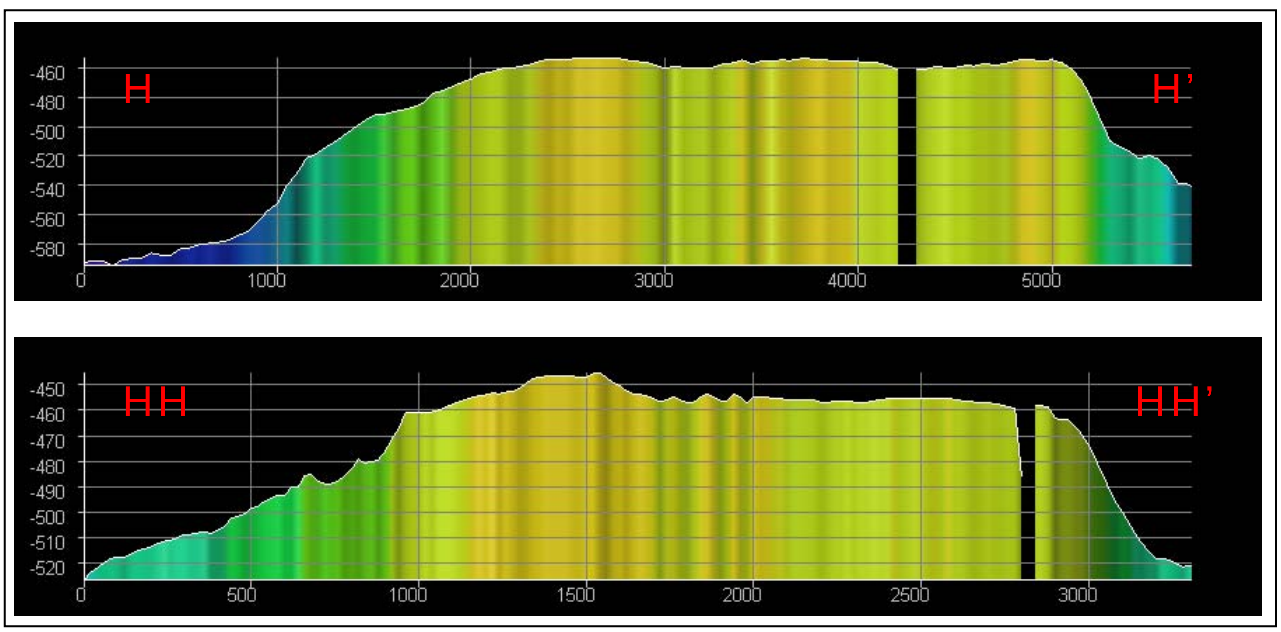


Figure 16H

hills is 100 m, as shown from A-A'. This is measured from the highest point on the profile to the break in slope at the 3000 m line. The profile line trending from B-B' reveals a height of 50 m, D-D' shows relief of around 60 m, and E-E' has about 70 m. The mounds have significant relief relative to the surrounding seafloor, but do not have large absolute relief. Tuyas typically show several hundred up to 1500 m in height and drumlins range between 10 to 75 m high. The seafloor hills are much closer to the height of drumlins.

Shapes of the Seafloor Hills in Profile

The profiles show that all of the seafloor hills show a very distinctly steep southern side with the exception of the two hills shown in Figures 20B and 20G. There is a significant break in slope from the sea floor on the six hills with a steep southern face. The northern sides are more variable, with some having steep sides and others having a much gentler northward slope. The hills that show a steep eastern slope are A, D, E, and H. Hills A, C, E, and H show both a steep northern and southern face. None of the hills show symmetrically steep sides, but are mostly all asymmetrical with a steep southern and/or eastern face and a tapering to the north. All of the hills show a relatively flat top. This is distinctive on all the hills in the east-west profiles. In the north-south profiles, many have only a portion of the top that is flat with the remainder sloping to the north.

Many of the seafloor hills have steep sides facing more than one direction, which is more similar to tuya morphology, which are surrounded by steep sides, than to drumlins, which have a single blunt, steep end. The flat tops are characteristic of tuyas, and not found on drumlins. The tapering profile of many of the hills, on the other hand, is most similar to a drumlin profile.

Shapes of the Seafloor Hills in Map View

Map view shapes of the hills are shown in Figure 17, with longest and shortest axes of 'best fit' circles or ellipses constructed. The axes and shapes were drawn based on the distinctive basal break in slope between each hill and the surrounding seafloor. Table 17.1 shows the ratio between the long and short axes and the orientation of the long axis for each hill. From these measurements only two of the hills show a circular form, A and C. The other six show an elliptical form in map view. The mean ratio of the eight hills is 1.3:1 and the mean orientation is N1°W. The shapes and axes of the relatively flat top of each hill were also constructed (Figure 18). The upper "plateau" of some hills vary in axial ration and orientation relative to the basal shapes (Table 18.1). There are a few outliers that make the mean orientation N20°E, but most show a N0°E trend of the long axis. The ratio between the long and short axes is similar to the basal break in slope ellipses, with an average of 1.39:1.

Compared to the morphology of drumlins (Figure 19), the seafloor hills do not have the typical, streamlined, teardrop shape. Three known tuyas in Iceland (Figure 24) have a near-circular to elliptical shape to them as shown by the imposed ellipses, more similar to the shapes of the seafloor hills.

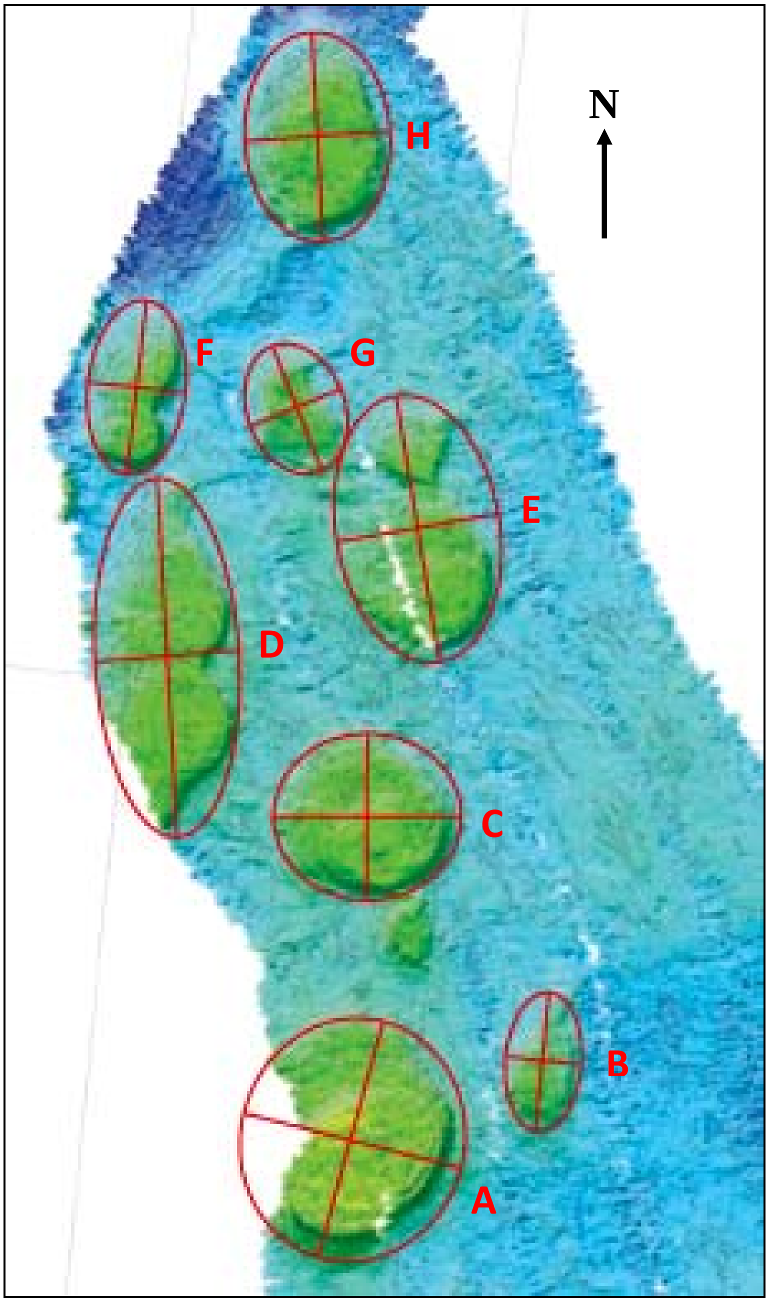


Figure 17: Enigmatic hills on the Ross Sea floor labeled A-H. They show subcircular to elliptical shape in map view.

Table 17.1

Seafloor Hill	Long Axis : Short Axis	Long Axis Orientation
A	1:1	N16°E
B	1.93:1	N6°E
C	1:1	N0°E
D	2.52:1	N5°W
E	1.66:1	N12°W
F	1.2:1	N6°E
G	1.4:1	N12°W
H	1.44:1	N4°W
Mean Values	**1.3:1**	**N1°W**

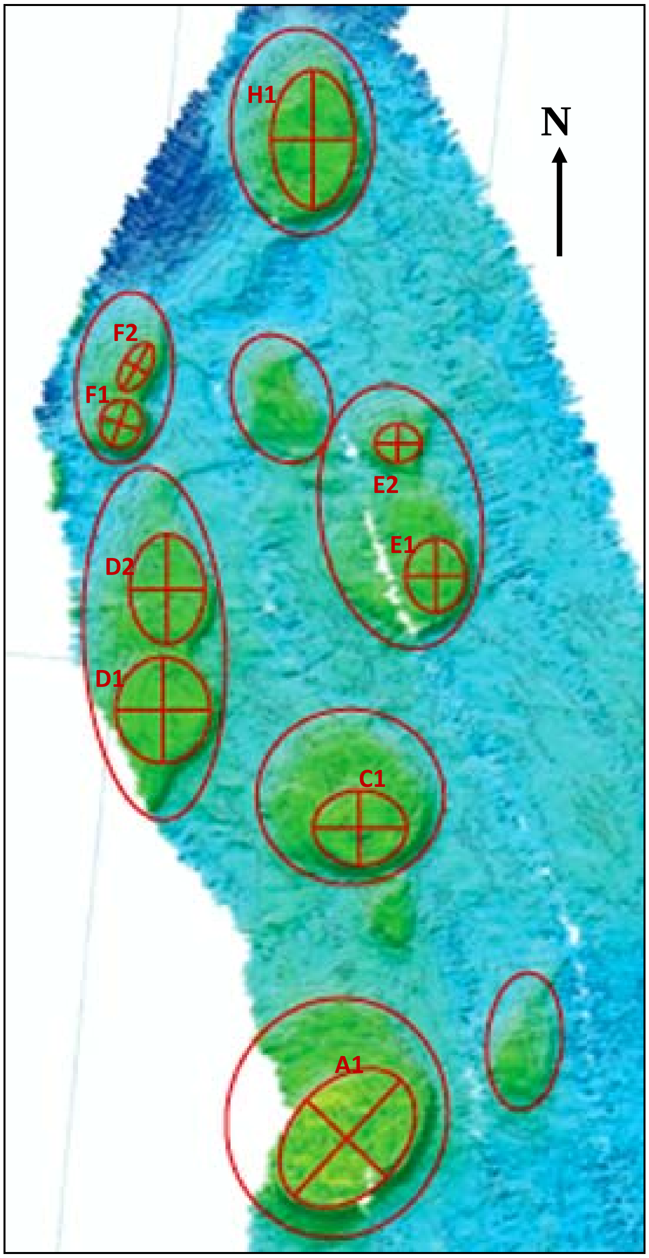


Figure 18: Upper contour long and short axes orientations.

Table 18.1

Seafloor Hill	Long Axis: Short Axis	Long Axis Orientation
A1	1.43:1	N44°E
C1	1.25:1	N90°E
D1	1.13:1	N0°E
D2	1.47:1	N0°E
E1	1.19:1	N0°E
E2	1.19:1	N0°E
F1	1.18:1	N21°E
F2	2:1	N31°E
H1	1.64:1	N0°E
Mean Values	**1.39:1**	**N20°E**

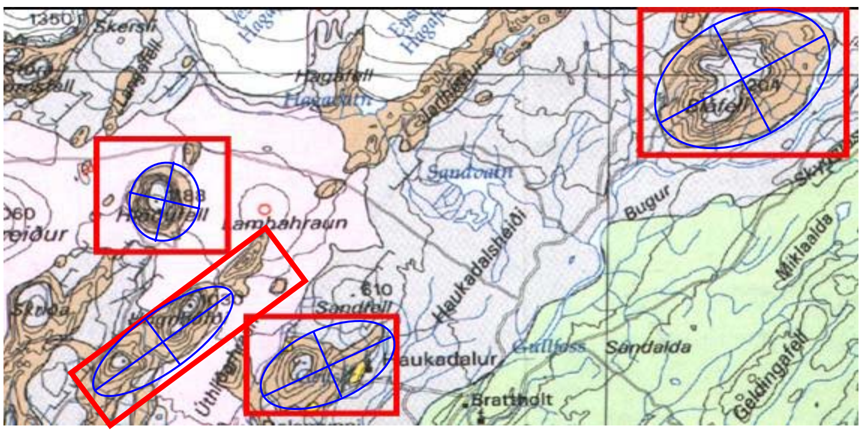


Figure 19: Topographic map of tuyas in Iceland. Note the subcircular to ellipsoidal shape. Modified from The Icelandic Institute of Natural History.

Discussion

Seafloor Hills Origin

The surface morphologies of the seafloor hills documented here do not provide a definitive test of the hypothesis for the origin of these seafloor hills; however, there are distinct characteristics that are similar to either a drumlin or tuya. The diameter of the elliptical hills is nearest to the size of a tuya, with the largest being 8 km along the long axis. However, the height of the hills does not appear to be to be consistent with the typical size of tuyas. The hill with the highest relief is 100 m and others fall in the range of 50 m – 90 m high. These height ranges correspond most closely to that of a drumlin, which are typically on the order of 10 m – 75 m tall. In map view, the hills look to be elliptical in form, which is a trait of tuyas or tindars. All of the hills show a decreasing slope to the north and west, but not to the extent of the streamlined drumlin form. A typical tuya has steep sides about the entire circumference of the hill and a flat top (Figure 20). Drumlins, in contrast, have a smooth, asymmetric profile, with a steeper, shorter slope changing at the summit to a longer, gentler slope (Figure 21). In the east-west direction, the seafloor hills closely resemble tuya morphology. In the north-south direction, however, the hills have an asymmetric profile that is somewhat similar to a drumlin. They differ in having a flat-topped portion of the summit, and some have sharp slope breaks on both northern and southern sides.

The hills show surface morphological features most closely related to tuyas, therefore they are most likely related to the known basaltic volcanism to the southeast. The western Ross Sea lies within the West Antarctic Rift System, where the extensional regime created normal faulting and a thinner crust. In a rift it is possible to have dikes propagating through the crust, and these could form the feeder conduits for the surface eruptions that formed the seafloor hills.

According to Rilling and others (2007) there is a wide range of ages for volcanic features on the seafloor along the Terror Rift of the Ross Sea. The new age dates of nearby Franklin Island from $^{40}Ar/^{39}Ar$ dating range from 3.28 to 3.73 Ma. However, there are significantly younger volcanic features on the seafloor that had volcanic activity age as young as 89 - 127 Ka. These young ages demonstrate that the seafloor volcanic edifices in the Terror Rift segment of the WARS are significantly younger than the volcanism that formed Franklin Island and other major volcanoes in the Erebus Volcanic Province. Although the ages for the seafloor volcanic features are older than the Last Glacial Maximum, regional ages show volcanism continued to the present.

Ice Sheet History

Ice sheet history and past ice coverage of this area of the western Ross Sea suggests that these seafloor hills may have had multiple interactions with ice sheet advances and retreats, depending on their age. An eruption subglacially would have the steep-sided, flat-top characteristics of a tuya, whereas glacial erosion would produce a tapered slope; these hills show both characteristics. The northward tapering slope of the hills suggest that the hill shapes may have been modified by erosion by a grounded ice sheet that rode over the top of them. This may be the reason that the seafloor hills show characteristic features of both tuyas and erosional drumlins. If the hills were shaped by erosion under grounded ice, the tapering of the hills can indicate flow direction. Shipp and others (1999) have documented the direction of ice sheet flow in this part of the Ross Sea during the Last Glacial Maximum from mega-scale glacial lineations (Figure 22). The nearest localities show an ice flow direction of NNE. The long-axes of the seafloor hills are oriented ~north-south and they taper to the north and west. This is similar to the regional ice sheet flow direction, and may be showing divergent ice flow around the southern end of the physiographic high and into and along the adjacent low basin (Figure 22). The subglacial erosion to form the tapered shape of the seafloor hills could be an indicator of the rate of flow in the area because drumlin formation is indicative of a boundary zone between slower and faster ice sheet flow (Wellner et al., 2001).

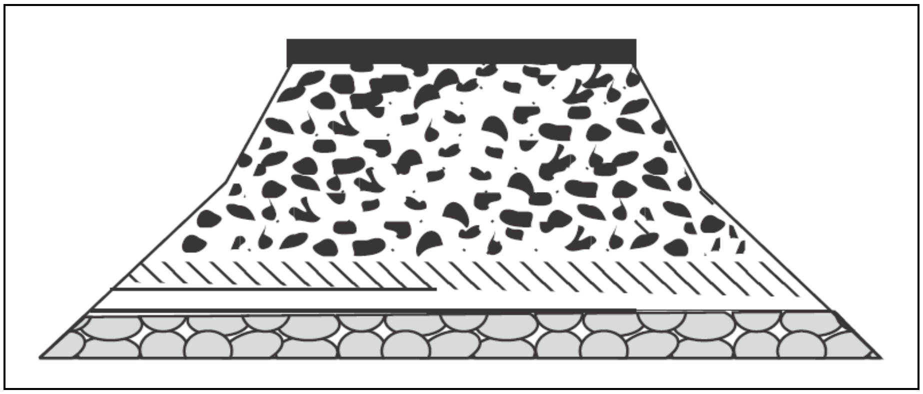


Figure 20: Cartoon of the horizontal profile of a tuya.

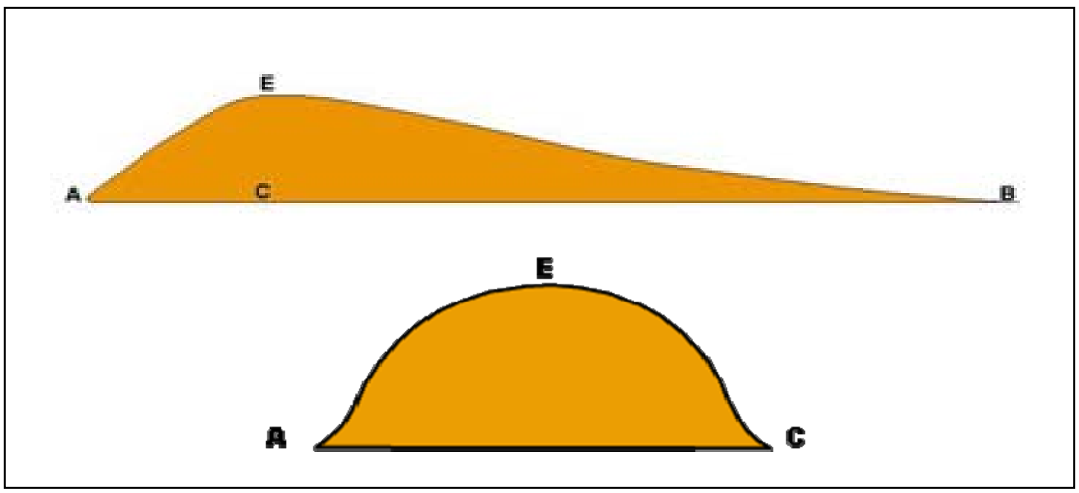


Figure 21: Cartoons of the long axis (top) and short axis (bottom) of a drumlin.

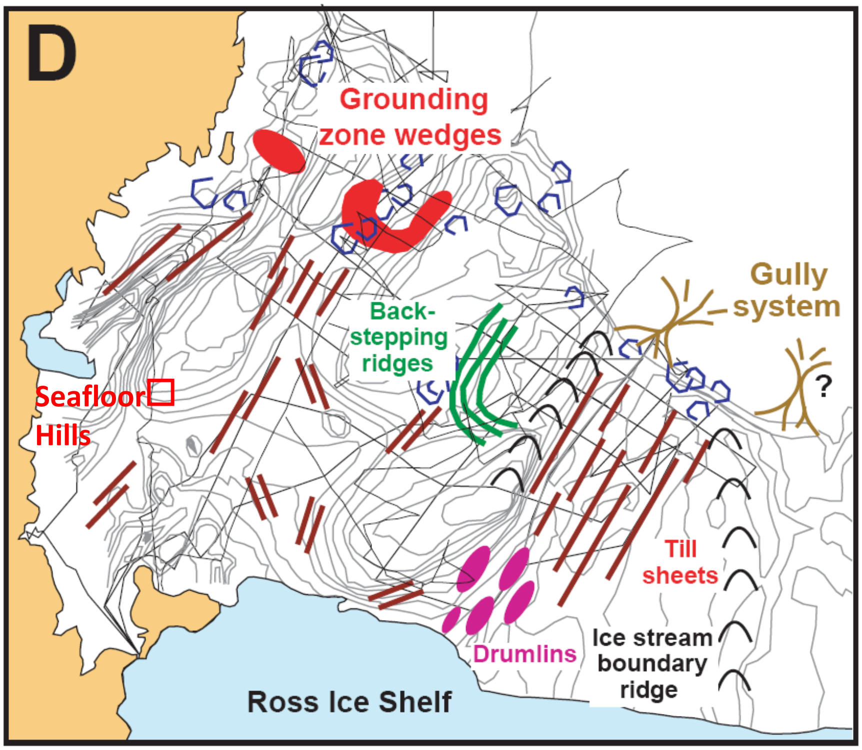


Figure 22: Location of ice flow indicators on Ross Sea floor. Modified from Shipp (1999).

Conclusions

The seafloor hills that were identified on the western Ross Sea floor are most likely volcanic in origin due to their similar surface morphologies to known subglacial eruptions. Their horizontal size, relatively flat tops, and sharp breaks in slope with steep sides are the features most similar to tuyas. If volcanic in origin, they are presumably related to the regional faulting and volcanism associated with the thinner crust and extensional regime of the Terror Rift. The fact that the long axes of the hills are generally parallel to the mostly north-south trends of faults within the Terror Rift (Hall et al. 2007) supports this hypothesis.

Since the hills do not have symmetrical steep sides, but have a northward slope and taper, it suggests that the hills may have been modified by erosion by a grounded ice sheet(s). Independent studies in this region of the western Ross Sea have shown ice flow directions to the north and northeast (Shipp et al., 1999), consistent with the long-axis direction of the seafloor hills.

Further study with alternative types of geophysical surveys can add new information to test the volcanic origin interpreted from morphological observations. Seismic profiling may show evidence of internal tuya stratigraphy and/or the signature of an intrusive conduit in the subsurface below the hills. Magnetic profiling can distinguish between sedimentary and volcanic rocks. Dredging of material from the seafloor hills can provide a definitive answer to their origin, and would also provide material to determine their age.

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